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STATE-OF-THE-ART REVIEW
OF
SOLAR PONDS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report provides a brief but concise review of solar pond technologies and their potential for application within the military. The report covers salt gradient solar ponds (SGSP), shallow solar ponds (SSP), saltless convecting solar ponds, gel ponds, viscosity stabilized ponds, and membrane ponds. In addition, several criteria were evaluated with respect to solar ponds. These included reliability, maintainability, efficiency, survivability, environmental impact and economics. Research and development requirements and ongoing activities were also summarized. This report documents one of several ongoing

state-of-the-art reviews of solar technologies performed by an Air Force liaison office with the Department of Energy.

PREFACE

This report documents work performed to determine the state-of-the-art of selected solar technologies. The report is based on literature available in the public domain and additional information and data obtained from representatives from various national laboratories and industries.

Opinions expressed in this report are those of the author and do not reflect the view of the Department of the Air Force or the Department of Energy. Citation of trade names or manufacturers does not constitute an official endorsement or approval of the use of such products.

This report has been reviewed and approved for publication by the Department of Energy and is releasable to the National Technical Information Service (NTIS) where it will be available to the general public and foreign nations.

William A. Tolbert

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STATE-OF-THE-ART TECHNOLOGY REVIEW
of
—SOLAR PONDS—
by
Captain William A. Tolbert, P.E.

1.0 INTRODUCTION

Solar ponds are one of the simplest and least expensive technologies for converting and storing solar energy. In fact, the solar pond is unique in its ability to act both as a collection and storage system. Solar ponds can be operated at virtually all habitable latitudes and can provide energy for space heating and cooling, industrial process heating and pre-heating, and power generation via an organic Rankine-cycle engine. In short, solar ponds have tremendous potential application for military bases—worldwide.

2.0 OVERVIEW OF THE TECHNOLOGY

Solar ponds can be either naturally occurring or artificially created bodies of water which both collect and store solar energy. Normally, a body of water collects a large amount of the sun's energy, but due to convective circulation, the energy is transported to the surface and lost. In solar ponds, various techniques are used to limit convection or heat loss and thus trap a substantial amount of energy within the pond.

For the purposes of this review, solar ponds will be classified into three basic categories:

- Salt Gradient Solar Ponds (SGSP),
- Shallow Solar Ponds (SSP), and
- Innovative Concepts.

2.1 Salt Gradient Solar Ponds (SGSP)

The most established type of solar pond is the salt gradient solar pond. A section of a SGSP is shown in Figure I. This type of pond has three distinct layers: the surface layer (containing small concentrations of salt), the non-convecting layer (containing an increasing salt concentration with depth), and the bottom convecting storage layer (containing a constant heavy concentration of salt).

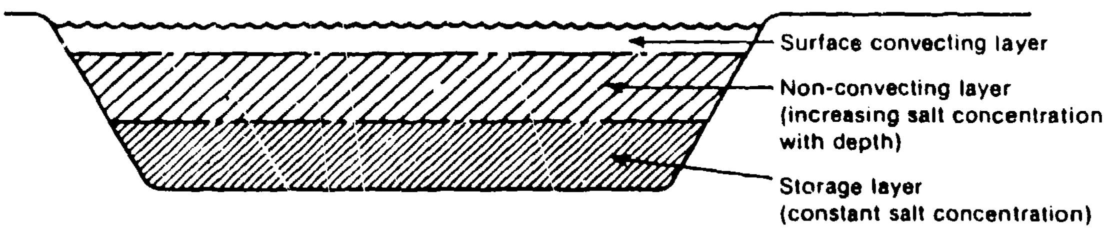

FIGURE 1: Salt Gradient Solar Pond

In the SGSP solar radiation is absorbed, both within the pond liquid and at the pond bottom, which is usually dark colored. The normal buoyancy effect of the wamer deep water is supressed by providing a higher density of dissolved salt in the lower layers of the pond. Usually SGSP are between one and three meters in depth and use NaCl or $MgCl_2$ salts. Thermal energy is normally extracted from near the top of the storage layer and reinjected through diffusers near the bottom of the storage layer. Under good conditions, the storage layer can reach the boiling point of the brine (100°C plus), while the surface layer remains at about ambient air temperatures due to evaporation and/or night sky radiation. The hot brine extracted from the pond is normally used in conjunction with a heat exchanger or closed loop system to lessen its corrosive effects. An in-pond heat exchanger presents less danger of disturbing pond gradients but poses additional maintenance problems.

Establishing and maintaining the salt gradient within the solar pond is currently considered something of an art. Once the brine layers have been established, the natural (but slow) diffusion of salt within the pond requires the periodic injection of concentrated brine at the bottom of the pond and fresh (or brackish) water into the surface layer.

SGSP can also be used in conjunction with organic Rankine-cycle engines. Figure 2 details the operation of a SGSP in a power generation configuration. Here the storage level provides a heat source for the evaporator side of the turbine while the surface layer provides a heat sink for the condensor side of the turbine. A pilot pond of 1 km^2 can produce approximately 5 MW of electricity. Although existing SGSP for power production are relatively small, projects involving natural and man-made ponds (lakes) in excess of several hundred km^2 are currently under study.

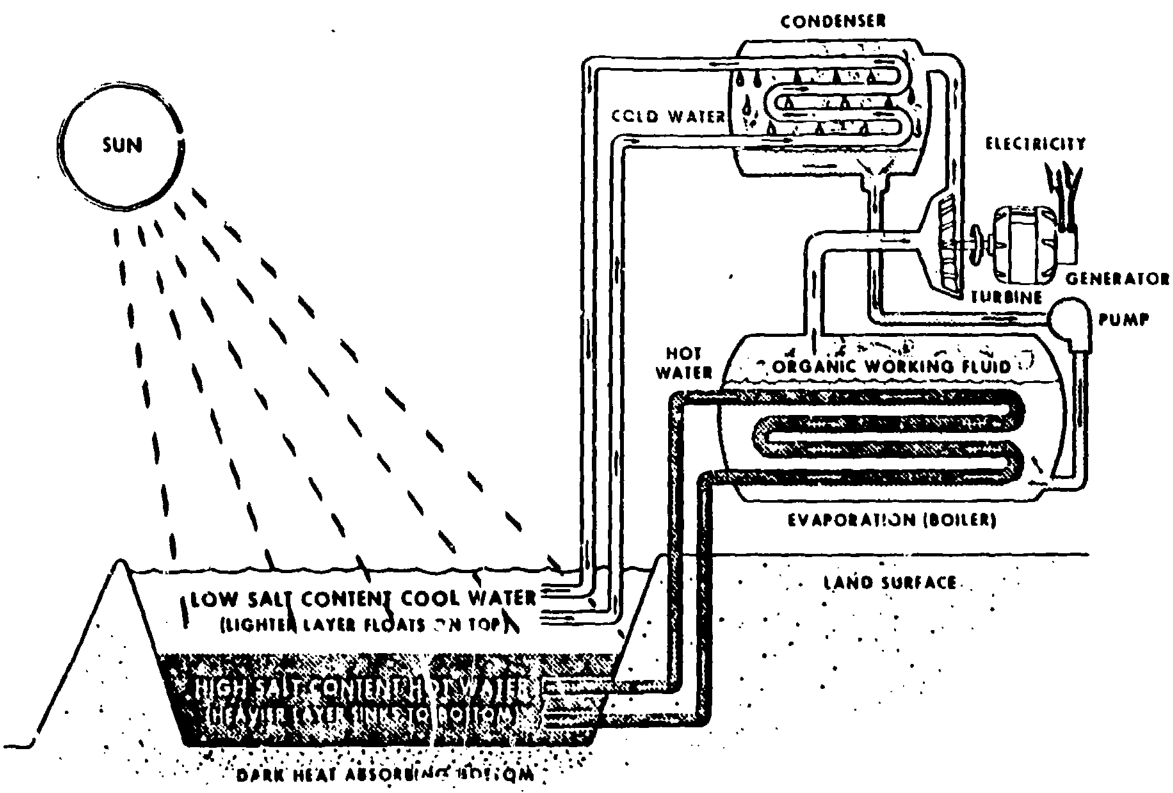

FIGURE 2: Solar Pond Generating Concept

2.2 Shallow Solar Ponds (SSP)

The SSP is more like a large low-cost site built solar collector than it is a pond. It consists of a plastic water bag within an insulated enclosure with a transparent glazing. A section of an SSP is shown in Figure 3. The SSP was developed to provide medium-temperature (40°C to 60°C) hot water in a batch mode. In the batch mode, SSPs are filled in the morning and drained into an insulated storage tank for subsequent use. SSP can also be operated in a continuous flow mode. Typical SSP modules are 5 m x 60 m with a water depth of about 100 mm. A major advantage of the SSP is that it can be located on rooftops if the structure provides adequate support. A disadvantage of the SSP is that it requires much additional plumbing and pumping equipment and separate nighttime thermal storage. SSPs are generally more expensive than deep solar ponds.

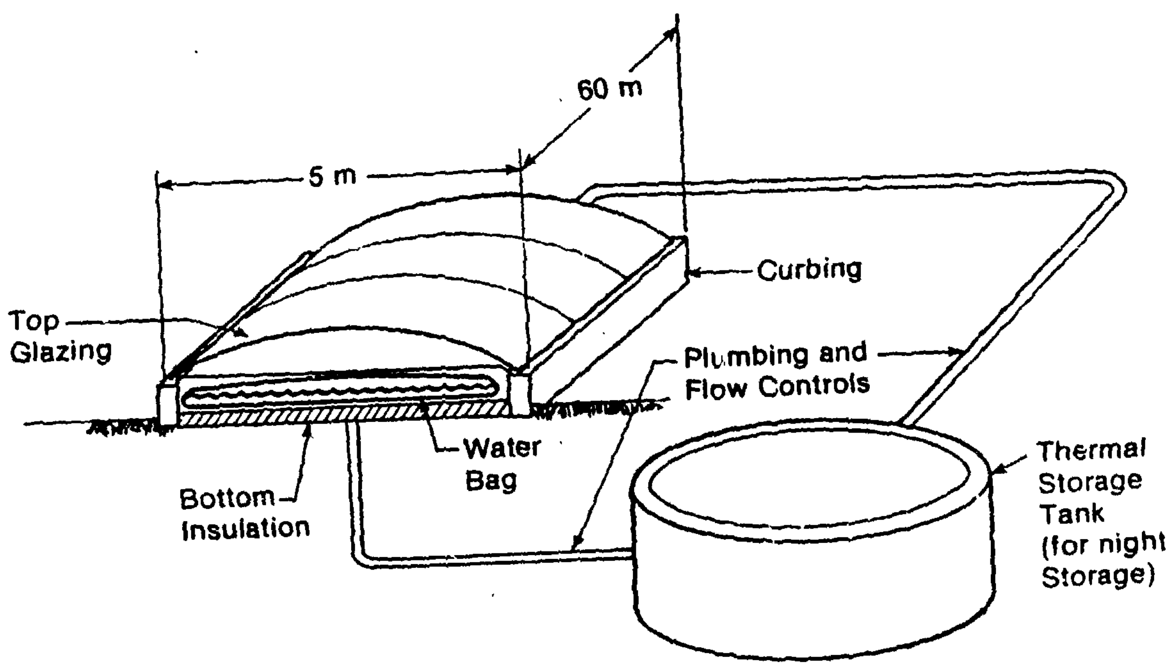

FIGURE 3: Shallow Solar Pond Design

2.3 Innovative Concepts

Several other pond concepts have also been proposed and are currently being evaluated for technical and economic feasibility. These "innovative concepts" deal with the convection and heat loss aspects of solar ponds in innovative ways. Some examples follow.

2.3.1 Saltless Convecting Ponds

The saltless pond resembles the SGSP except that salt gradients are not used to inhibit convection. Instead, the pond is protected from thermal loss by the use of transparent covers and/or the use of night insulation. Possible covers and insulation include floating microglass beads, inflated plastic film glazings, the use of a transparent polymer gel blanket, liquid foam, or closeable lids.

2.3.2 Gel and Viscosity Stabilized Ponds

These ponds rely on the addition of various substances to the pond water to increase the viscosity to the point where convection is suppressed, or where the entire pond gels to a semi-solid.

Another "gel pond" concept is being developed which uses a non-toxic, transparent, floating polymer gel. This gel is heavier than water but lighter than brine and floats on the top of 20% brine solution in a pond. The gel is formed onsite by mixing appropriate liquids and pumping the mixture onto the top layer of the saline water before the reactions are completed. The solid then acts as a thermal insulation material, prevents evaporation, and avoids the problems associated with maintaining salt gradients.

2.3.3 Membrane Ponds

In these ponds, transparent membranes are use to suppress convection in the pond. These membranes can be inserted in either horizontal or vertical planes.

3.0 POTENTIAL APPLICATIONS

Solar ponds have a tremendous potential for displacing fossil fuels at military bases worldwide. Solar ponds are readily applicable to low- and medium-temperature (25°C to 100°C) uses such as:

- Space Heating,
- Water Heating,
- Absorption or Desiccant Cooling,
- Industrial Process Heating,
- Industrial Process Pre-Heating, and
- Electric Power Generation.

4.0 DISCUSSION

In order to accurately assess the application potential to the military of solar pond technology, several "criteria" should be further discussed.

4.1 Reliability

Because of the massive thermal storage which the solar pond provides, the start-up (charging) time is very long (several months). The typical solar pond takes weeks for a 10°C temperature rise, but is virtually insensitive to inclement weather. In fact, a pond can freeze over during the winter and still collect and supply useful heat from its storage layer. In effect, the solar pond converts an intermittent energy source—sunshine—into a reliable source of thermal energy.

In SGSP applications, practical factors which affect system reliability include the problems associated with the maintenance of salt gradients. High winds (wave motion), heat extraction mechanics, and boiling can sufficiently disturb the gradients and reduce the efficient operation of a pond. These factors however can be adequately designed for and controlled.

4.2 Maintainability

Solar ponds are among the simple solar systems to operate and maintain. The annual manpower required is normally less than that associated with a conventional plant of similar size. Maintenance factors include the periodic salt gradient maintenance identified in Section 2.1, corrosion control procedures associated with piping and equipment, inspection and repair of the pond liner (if one is used), and the control of biological growth by occasional addition of biocides.

In general, once a pond is in operation the skills required to maintain it are typical of those used to maintain military hydronic heating systems.

4.3 Efficiency

Solar pond systems represent a low-cost, low-efficiency technology. The efficiency of a solar pond for heating is about 10% to 20%, and the efficiency for electrical production drops to 1% to 2% (insolation to electrical output). In addition, parasitic losses average 5% of the energy produced for heating applications and 20% of the energy produced for power applications. In spite of these low efficiencies, solar ponds can be economical in many areas because of their low cost.

Also, because of its massive storage, temperatures, the solar pond may require no backup for many space heating, hot water and low-temperature industrial process heat applications depending on local climatic conditions.

4.4 Survivability

The survivability of solar ponds is directly related to the maintainability of the salt gradients in different threat environments. Previous military research in this area indicates that solar ponds are more survivable in natural disaster (earthquake, high winds, etc.) threat environments than other alternate energy systems. They are however more susceptable to sabotage and weapons effects.

It should also be noted that after exposure to any of the threat scenarios, solar ponds would continue to operate even though the efficiency will have been lowered. This is not the case with many other solar systems (i.e., WECS, PFDR, LFDR, etc.).

4.5 Environmental Impact

The environment impact of SGSP or gel ponds would be related to the containment of the salts or chemicals associated with the operation of these ponds. Liner leak detection systems could be used to prevent significant contamination of soil or ground water systems in the area of these ponds.

In addition, all ponds impact their environments with respect to localized ground heating and require safety precautions normally required around high-temperature sources.

4.6 Constraints

Solar pond applications are inherently constrained by the following:

- land availability,
- water availability,
- salt or brine availability,
- soil conditions,
- local topography, and
- meteorological conditions.

4.7 Economics

Although solar ponds have a low overall efficiency among solar technologies, their extremely low costs can make them very economical as well.

Since salt ponds require approximately 1/2 ton of salt per square meter of pond surface area, to a great degree the economics of salt ponds is a function of the cost of salts. In fact, one-third of the construction cost of a SGSP system can be salt costs alone. Land, excavation, and liner costs represent the other major cost components.

Typical deep solar pond capital costs are \$30 to \$75 per square meter with typical costs of energy ranging from \$1.61/MBtu at optimum locations to \$5.02/MBtu at moderate sites and \$12.00/MBtu at poor sites. A specific example is the SGSP at Miamisburg, Ohio which cost \$35/m^2 and is projected to deliver heat at about \$9.45/MBtu.

Typical shallow solar pond costs are estimated at \$50 to \$100 per square meter.

Innovative concepts are expected to add between \$1 and \$10 per square meter to the costs of a basic solar pond.

In extremely large natural solar pond projects designed to produce power the cost of the electricity is projected to be between 6¢ and 13¢ per kilowatt hour.

Since limited actual operating experience exists for solar ponds, O&M costs and lifetimes can only be estimated to be equal to that of flat-plate solar thermal collector systems.

The Israelis feel that a 1 km^2/5 MW_e natural pond will require two man-years per year for maintenance.

5.0 OPERATIONAL EXPERIENCE

Based on operational experience in both the U.S. and Israel, it has been established that the salt gradient solar pond is a viable technology. The Israelis have had the most visible success with their 7000 m^2 pond completed in 1979 at Ein Bokek on the Dead Sea. This pond generates over 150 kW of electricity on an intermittent basis, and exemplifies the focus of the Israeli pond program on large-scale baseload electricity generation.

Several experimental ponds in the U.S. have been operated for actual or simulated thermal uses. These ponds are highlighted in Tables I and II. Because solar pond research has only been underway in this country for the past six years, operational and cost data is still limited although many materials, construction, and operations lessons have been learned. Technical problems encountered are listed in Table III.

6.0 CURRENT STATUS

Solar pond technology can not yet be considered a fully proven technology for several reasons:

- Actual measured efficiencies of experimental ponds (9% to 12%) are substantially below the 20% to 30% efficiencies predicted by thermal calculations.
- Entire pond systems (pond plus application) have not yet been operated, for example, a pond driving an absorption chiller.
- Long-term performance experience is not available.
- Ponds are subject to substantial economies of scale and only small ponds have been actually operated.
- R&D needs exist in several areas (see Table IV).

The objective of the U.S. Solar Pond Program, under the U.S. Department of Energy, is to establish ponds as a proven cost-effective technology. The program started under the early ERDA solar effort with primary applications being space heating and low-temperature industrial process heat. As pond technology advances, higher temperature applications such as space cooling and thermal power generation will be developed.

It appears that solar pond R&D is going on in various areas including basic research (6.1), exploratory development (6.2), advanced development (6.3), and engineering development (6.4). Primary military interest should be centered on engineering development of prototype systems so that large-scale applications in the FY1984 or FY1985 MCP timeframe can be developed. Because of current and projected pond economics and the extensive low-temperature energy requirements found in the military, it is recommended that military facilities energy programs focus on thermal rather than power applications of ponds.

Several military applications of solar pond technology are currently under study and/or design. These include:

- Feasibility study of using a 5-15 acre salt gradient solar pond at the U.S. Air Force Academy for providing space heating and absorption air conditioning. The pond would totally replace one of the existing N.G./oil fired central heating plants at the Academy.
- Design and planned construction of over 250,000 sq. ft. of shallow solar ponds at Fort Benning, Georgia for generation of 500,000 gallons per day of domestic hot water.
- Conceptual design of a series of solar ponds within the Truscott, Texas brine impoundment lake for the Army Corps of Engineers. The 135 acres of salt gradient solar ponds would provide electrical power for pumping brine from the Red River Valley of Texas.
- Feasibility study of using Navy property adjacent to the Salton Sea for a large power generating plant (600 MW_e) to provide power in southern California.
- The evaluation of using solar pond technology for providing low-temperature industrial process heat for a military installation.

7.0 R&D ORGANIZATIONS/ACTIVITIES

The Solar Energy Research Institute (SERI) has lead in solar pond thermal applications, including IPH and space heating, and experience in salt gradient solar ponds and innovative concepts.

Jet Propulsion Laboratory has lead in large-scale pond Rankine-cycle power applications and resource assessments.

Lawrence Livermore Laboratory has lead and experience in shallow solar ponds.

Los Alamos National Laboratory has experience in laboratory tank and hydrodynamic stability experiments.

Argonne National Laboratory has experience in pond modeling and pond operations.

University of New Mexico, Albuquerque, has experience in SGSP and gel ponds.

8.0 CONCLUSION

Solar pond technology is in its infancy but has already demonstrated that it is a simple and economical technology for converting and storing solar energy for use in thermal or power applications. In general, solar ponds are reliable, are easy to operate and maintain, have good survivability characteristics and offer potentially excellent economics despite their low overall efficiencies. Although solar ponds are a working technology, limited operational experience prevents their classification as a fully proven technology. Significant opportunities currently exist for increasing the performance and economics of solar ponds so that they can be ready for military-wide applications. Because of the wide range of possible applications for solar ponds and because of the substantial low- and medium-temperature thermal energy requirements on all military bases, solar ponds have tremendous potential for near-term military application. The key to large-scale, military-wide applications of this technology in the FY1985 timeframe is to ensure that critical exploratory, advanced, and engineering development issues begin to be addressed immediately.

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TABLE I. Current Salt Gradient Pond Projects

Contractor/Loc.	Area	Depth	Key Objectives	Achievements/Problems
U. of NM Albuquerque	167 m^2	2.5 m	Gradient maintenance, heat extraction, stability with NaCl	Boiling temp reached; annual thermal efficiency only 8%, sloping walls give convection
Ohio State Univ. Columbus	200 m^2-old 450 m^2-new	2.5 m 2.5 m	Test boundary migration, stability, measure perimeter heat loss, test reflectors	Successful heat extraction, grain drying demonstration; wind blown debris reduced clarity
DOE Mound Lab Miamisburg, OH	2,000 m^2	3.0 m	Provide heat to city recreational building and swimming pool	Successful operation for one year; costs: \$35/m^2, \$5.45/MBtu (ten-year life)
Ohio AG R&D Center Wooster	155 m^2	3.0 m	Greenhouse heating, test cover and reflector, heat pump source	Chemical treatments developed to maintain clarity; leaks due to design and materials
Desert Research Inst. Boulder City, NV	10 m^2	1.0 m	Investigate feasibility of saturated ponds using $MgCl_2$, $CaCl_2$ and borax	Borax pond self-starting, demonstrated superior stability; algae problems, salt precipitation makes bottom white
Intertechnology Corp. Warrenton, VA	1 m^2	1-2 m	Lab-scale feasibility of saturated pond using sodium carbonate-bicarbonate salt	New project - no results yet

TABLE II. Shallow Solar Pond Projects

Project/Location	Area	Application	Status/Problems
Sohio Petroleum Co. Grants, NM	6 acres (Projected)	Uranium Ore Processing	Construction costs made system uneconomic; project currently on hold
Sweet Sue Kitchens Athens, AL	1,600 m^2 (Projected)	Chicken Packing	Potable water required HEX; small size made cost/unit area high; project cancelled by DOE
Ft. Benning, GA	25,600 m^2	Hot Water for Barracks and Laundry	2 million liters/day; est. cost \$95/m^2; detailed design by A/E in progress, start construction June 1980, finish December
Ft. Gordon August, GA	10,000 m^2	Barracks Hot Water	Rooftop ponds; preliminary design phase

TABLE III Technical Problems and Approaches

PROBLEMS	APPROACHES
Prevent Convection	1. NaCl salt gradient 2. Other salts where cheap (e.g., bittern) 3. Saturated solutions (ongoing research) 4. Gels (no promising candidates at present) 5. Membranes
H_2O Clarity	1. Copper sulphate (for algae) 2. Chlorine (for bacteria) 3. Selective precipitation for minerals 4. Fences and surface flushing for debris
Heat Extraction	1. In-pond heat exchanger 2. Optimize hot brine withdrawal for large ponds
Slow Migration of Layer Boundaries	1. Model pond and full-scale experiments 2. Theoretical and numerical hydrodynamic studies
Surface Layer Growth	1. Model pond and full-scale experiments 2. Understand effect of diurnal heating and cooling plus surface evaporation 3. Theoretical and numerical hydrodynamic studies
Wind Driven Instabilities	1. Wave break may prove adequate Problem needs theoretical hydrodynamic study
Scale Up to Many Acre Pond for IPH or Electricity	1. Field experiments including design studies 2. Establish maintenance requirements and cost
Salt Pollution	1. Liners for small ponds 2. Natural saline environment or impervious soil for large ponds 3. Recycle diffused salt
Pond Lifetimes	1. Test and develop improved materials

TABLE IV

RESEARCH AND DEVELOPMENT REQUIREMENTS

- Hydrodynamic studies - gradient layer stability, gradient layer erosion by top and bottom mixed layers, surface layer effect (wind, precipitation, evaporation, radiation), and wave control.
- Evaporation control - by covers or surface liquid films.
- Water clarity - methods to prevent clouding by dirt, blown debris, algae, mineral precipitates, organic matter.
- Alternate salts - locally available, e.g., from mining wastes or stack scrubbers - low or zero cost.
- Salt gradient - recycling methods, leak detection, emergency brine storage.
- Heat exchangers - lower cost, corrosion and fouling prevention, direct contact alternatives.
- Maintenance procedures - simple, standardized, low cost.
- Survivability testing.

R&D Needs for Natural Ponds, Which Tend to be Larger in Size Include:

- Soil impermeability treatment - to eliminate need for liners.
- Cheap, large-scale diking methods.
- Prevention of organic matter decomposition under the pond, leading to bubbles.
- "Floating Ponds" - for deep natural salt water bodies - no solid bottom.

R&D Needs Specific to Constructed Ponds, Which Tend to be Lined and Smaller, Include:

- Liners - high-temperature stability, UV resistance, reliable seam connections, repairable in place, lower in cost.
- Cheap excavation techniques.
- Side heat loss effects.
- Brine extraction without penetrating the liner.